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MEASUREMENT OF SEA ICE DRIFT FAR FROM SHORE USING LANDSAT AND A--ETC(U)
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A semi-automatic procedure for transferring the location coordinates of a common set of ice features from the Earth coordinate system of one LANDSAT image to another is discussed. Errors in the transferral technique are examined using imagery over land and are found to be dominated by deviations (as large as 8 km) in the actual position of the center of the image from its stated position. A least-squares strain program which utilizes polar coordinates to eliminate spurious effects that may occur if the coordinate system of

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20. Abstract (cont'd)

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a given floe is used as the common coordinate system, is discussed. The use of uncontrolled aerial photography to measure sea ice strain results in errors of the order of 1%.

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MEASUREMENT OF SEA ICE DRIFT FAR FROM SHORE USING LANDSAT AND AERIAL PHOTOGRAPHIC IMAGERY

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ABSTRACT

This paper discusses recent work on the development of analysis procedures for obtaining drift and deformation measured from sequential visual imagery of sea ice that is located far from land. In particular for LANDSAT images far from land a semi automatic procedure for transferring the location coordinates of a common set of ice features from the Earth coordinate system of one image to another is discussed. Necessary inputs for the transfer are the location coordinates (latitude and longitude) of the center of each image and the location of two arbitrary points on a known line of longitude; all this information is available from LANDSAT, although with some error. Errors in the transferral technique are examined using imagery over land and are found to be dominated by deviations (as large as 8 km) in the actual position of the center of the image from its stated position. The errors on the average are, however, less than typical one day ice drift distances. The LANDSAT image location errors also introduce uncertainties in the orientation of the coordinate systems after transfer. These errors will produce spurious apparent strains if velocities are estimated by simply taking position differences. This subtle effect may also occur if the coordinate system of a given floe is used as the common coordinate system. A least-squares strain program utilizing polar coordinates, which eliminates such spurious effects, is discussed.

With regard to measuring strain from sea ice aerial imagery without ground control, errors in such measurements are examined using uncorrected photographs obtained during April 1975 by NASA using a

RC-8 camera over the main AIDJEX camp. During the time of the photographic flights a ∼7 kilometer "calibration" line was monitored on the ground. The errors in using such uncorrected imagery and using common undeformed ice floes to establish a common scale are found to be of the order of 1% whereas typical maximum differential motions are as large as 5%.

INTRODUCTION

One use of the satellite and aerial imagery of considerable importance for modelling studies is the estimation of sea ice drift and deformation by using sequential overlapping images. Such a use of LANDSAT imagery near land has been discussed by a number of authors (eg. Crowder et. al., (1974); Shapiro and Burns, 1975). In these papers the basic procedure has been to identify common features on sequential images so that relative distance changes can then be measured. If some points on the image of interest are on land then drift rates in addition to deformation rates may be estimated since the land points do not move.

However, when LANDSAT images far from shore are used for analysis, the problem of obtaining both drift and strain rates becomes considerably more difficult. The principal difficulty with drift rate estimation is that no immovable land points are available for "calibration" and consequently one has to use the coordinates of the centers of the images as well as available longitude marks to fix the image locations. In principal the problem of drift then becomes one of first projecting common ice features (on sequential images) onto the spheroid and then back onto a common tangent plane. A somewhat more useful procedure, which we will discuss in this paper, is to transfer the coordinates of both images (considered to be tangent planes) onto a common intermediately located, tangent plane. In practice, such a procedure simply consists of appropriately translating and rotating the polar coordinates of all points in sequential images to the coordinate system of the first image.

The estimation of the strain rate, on the other hand, is dependent in a more subtle way on the transfer of coordinates from one image to another. The key problem here is caused by spurious rotations of the coordinate system that can be induced by errors in longitude lines. Such spurious rotations can also be induced by using a common rotating floe to establish a common coordinate system. The basic problem is that if velocities are estimated by merely subtracting location coordinates in a rectangular coordinate system then such spurious rotations will induce concomitant errors in the diagonal components of the strain rate tensor. Such undesirable effects can be avoided by using an appropriate least-squares strain program in polar coordinates, an example of which will be discussed later.

In the following we will discuss procedures used to estimate the drift and deformation of sea ice from LANDSAT images of areas located far from land. We then briefly examine some results obtained from uncorrected aerial imagery photographed from 9144 m (30,000 ft) altitude.

Drift Rate Estimation

In principle, if the center locations of two sequential overlapping LANDSAT images are known, then drift rates may be estimated by identification of ice features common to both images. One way to do this is to transfer the coordinates from the image planes onto the spheroid, and then onto a common plane. Such a procedure is, however, relatively complex. A simpler procedure, adequate for LANDSAT imagery is to assume that both images are effectively co-planar so that the transfer of coordinates becomes a simple translation and rotation in a given plane.

In particular it is convenient to assume that both images are in the plane whose perpendicular is given by the cross product of the two north vectors tangent to the earth at latitude θ, and parallel to the longitude lines ϕ and ϕ'. The angle between these two vectors defines the angle between the x-axes of the two image coordinate systems for image centers on the same latitude line. For simplicity we also take this angle to be the same if the second image is on both a different longitude line and a different latitude than the first, an assumption inducing errors of order d^3/R^2. By taking an inner product, the angle between these two vectors γ, is given by

$$\gamma = \cos^{-1}\left\{\cos^2\theta + \sin^2\theta\cos[\phi'-\phi]\right\}$$

For small values of $(\phi'-\phi)$ this expression reduces to

$$\gamma \simeq \cos^{-1}\left\{1 - \frac{[\phi'-\phi]^2}{2}\sin^2\theta\right\}$$

$$\simeq \cos^{-1}\left\{\cos[(\phi'-\phi)\sin\phi]\right\} = [\phi'-\phi]\sin\phi$$

With the above assumptions the geometry for the coordinate transfer is given in Figure 1, where points 1 and 2 are the centers of images 1 and 2 respectively. The angle of rotation between the coordinate systems is given by γ and the translation distance is defined by the chord distances D_1 and D_2 along the latitude and longitude lines. The values of D_1 and D_2 can be calculated from the expressions:

$$D_1 = \frac{2\sin\left[\frac{\phi'-\phi}{2}\right]}{[\phi'-\phi]} D_{LAT}$$

$$D_2 = \frac{2\sin\left[\frac{\theta'-\theta}{2}\right]}{[\theta'-\theta]} D_{LONG}$$

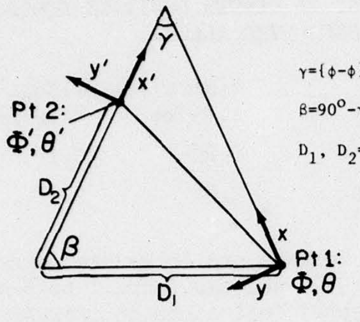
where D_{LAT} is the distance on the International Spheroid between longitude ϕ' and ϕ measured along latitude line θ, and D_{LONG} is the international Spheroid distance between latitudes θ' and θ measured along longitude line ϕ'. Approximate expressions for these distances are given on page 1187 of Bowditch (1958).

In order to give an idea of the errors induced by the approximations in the coordinate transfer procedure, we have compared the distance and angles between a number of points obtained using our LANDSAT projection procedure for both a sphere (referred to as the LANDSAT SPHERE) and the International Spheroid (referred to as the LANDSAT SPHEROID) with the results obtained by using a planar projection onto a fixed plane tangent to point 1. For the spherical cases, we considered point 1 to be at lat 80°, long 0° and have also considered 9 other points, 3 located along lat 80° at increasing distances toward the west, 3 located along long 0° at increasing distances toward the north and 3 located at increasing distances toward the northwest. The results are summarized in Table I with positive angles being measured in a clockwise direction from the x (north) axis. Point 1 is taken to be the origin. In the spherical calculations a radius equal to the average radius of the International Spheroid was used. The great circle distance was computed using the spherical surface. In general, Table I shows that there is very little difference between the various projections with the maximum difference being about 1 km at 600 km. In actual practice the maximum transfer distances are rarely greater than 250 km so that differences in the various projections are hardly significant.

In order to test the transferral technique in actual practice we utilized a number of overlapping LANDSAT images of Alaska. From pairs of such images common land features were identified and their coordinates were transferred from the second image to the coordinate system of the first image. Because the points were "immovable", apparent motions could be identified as errors.

After examination of a number of such image pairs it became apparent that the dominant source of error in the coordinate transfer was caused by deviations between the actual location of the center of the image and its stated location. On the average these positional inadequacies induced errors of the order of one kilometer.

The actual errors obtained from a series of 6 photo pairs are given in Table II. In this table rms errors before and after correcting the location of the center position are given. The center positions were corrected by overlaying the images on accurate survey maps with a zoom transfer scope. As can be seen from Table II, using the actual center position improves the translation errors by about half a kilometer on the average. The actual errors, however, between the true and stated center location can be as large as 8 km. This is illustrated in Table III, which summarizes the center position errors of 17 photographs. The maximum deviation observed was 8.12 km (in the



$\gamma = \{\phi - \phi\} \sin\theta$

$\beta = 90^{o} - \gamma/2$

D_1, D_2 = Chord distances along latitude and longitude lines

Figure 1. GEOMETRY FOR "LANDSAT" PLANAR TRANSFERRAL

TABLE I. COMPARISON OF PLANAR AND LANDSAT PROJECTIONS.

Location of initial pt. 80°N, 0°W.
Radius of Reference Sphere was 6371.299 km

Location of Final Pt		Great Circle Distance	LANDSAT SPHERE Projection		Planar Projection using Sphere		LANDSAT SPHEROID Projection using International Spheroid*	
Long	Lat	Distance	Angle	Distance	Angle	Distance	Angle	Distance
0°W	81.2°N	133.439 km	0°	133.436 km	0°	133.429 km	0°	133.572 km
0°W	82.6°N	289.117	0°	289.092	0°	289.018	0°	289.414
0°W	85 °N	555.995	0°	555.819	0°	555.290	0°	556.415
6°W	80 °N	115.806	-87.046	115.804	-87.045	115.799	-87.044	115.932
14°W	80 °N	269.681	-83.106	269.661	-83.105	269.600	-83.105	269.959
25°W	80 °N	479.030	-77.690	478.917	-77.684	478.579	-77.688	479.446
6°W	81.2°N	172.110	-36.308	172.113	-36.302	172.089	-36.310	172.294
14°W	82.6°N	370.874	-32.413	370.915	-32.390	370.693	-32.411	371.323
25°W	85 °N	651.477	-21.262	651.759	-21.152	650.342	-21.261	652.459

*The parametric latitude values of the points used for the spherical calculations were converted to geographical latitude values for use with. the Spheroid program.

TABLE II. RMS TRANSLATION ERRORS.

Photo Pair	Before Center Position Correction ΔX(North)	ΔY(East)	After Center Position Correction ΔX(North)	ΔY(East)
1	1.66 km	1.14 km	.37 km	.11 km
2	2.14	.49	1.22	.49
3	1.63	.49	.72	.15
4	2.43	.24	.53	.13
5	.55	.11	.55	.58
6	.17	.25	.20	.24
Average	1.43 ± .89	.45 ± .37	.60 ± .35	.28 ± .20

TABLE III. SUMMARY OF CENTER POSITION ERRORS FOR 17 IMAGES OVER ALASKA.

	X(North)	Y(East)
Max. Deviation	1.73 km	8.12 km
Min. Deviation	0.20	0.19
RMS Deviation	0.84	3.50

east-west direction). These numbers are in general agreement with the study by Colvocoresses (1974) who has found 1 to 8 km errors in the latitude and longitude center indicators on LANDSAT photos.

The reason that such center errors do not induce greater errors in the transfer appears to be due to the consistency of the offset errors; that is, pairs of photos will have similar errors in both the magnitude and the direction of their center positions. However, there is no assurance that the updating of orbital parameters will not be made in the middle of a sequence.

Deformation Rate Estimation

A convenient way of estimating least-squares strain rates and vorticity has been to note that the x and y ice velocities at position i, (u_{x_i}, u_{y_i}) are related to the strain rate and vorticity by (assuming a linear velocity field)

$$\begin{aligned} u_{x_i} &= x_i\,\dot{\varepsilon}_{11} + y_i\,[\dot{\varepsilon}_{12} - w] + A_1 \\ u_{y_i} &= x_i\,[\dot{\varepsilon}_{12} + w] + y_i\,\dot{\varepsilon}_{22} + A_2 \end{aligned} \qquad (1)$$

where $\dot{\varepsilon}_{ij}$ is the strain rate defined by

$$\dot{\varepsilon}_{ij} \equiv \frac{1}{2}\left[\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i}\right]$$

and w is the vorticity defined by

$$w \equiv \frac{1}{2}\left[\frac{\partial u_2}{\partial x_1} - \frac{\partial u_1}{\partial x_2}\right]$$

A complete discussion of the application of least-squares equations of this type to sea ice deformation is given in Hibler et al. (1974). This approach has the advantage that the velocity points further apart automatically affect the strain-rate estimates more than do velocities of points close together. Also the vorticity is computed in a normal least-squares way.

A drawback to this approach is that if velocities are estimated by merely subtracting location coordinates in a rectangular coordinate system errors will be induced in the strain rate by spurious rotations of the coordinate system. The basic problem can be easily visualized by examining Figure 2. In it we consider three points, which are stationary relative to one another and consequently undergo zero strain. Using the three relative distances between these points we would in fact find a strain rate of zero for all components of the strain rate rensor. However, using rectangular coordinates and equations (1) we would obtain, for a clockwise rotation of θ radians per unit time, the strain rates and vorticity:

$$\dot{\varepsilon}_{12} = 0$$

$$\dot{\varepsilon}_{11} = \dot{\varepsilon}_{22} = \cos\theta - 1$$

$$w = \sin\theta$$

or for a 3° rotation $\dot{\varepsilon}_{11}=\dot{\varepsilon}_{22}= -1.37.10^{-3}$ per unit time. A consistent way around this problem is to calculate the coordinates and velocities of the points in polar coordinates using as the direction of the unit $\hat{r}$ and $\hat{\theta}$ vectors the initial polar coordinates of the points. In particular, if the initial and final positions of a point are given by the polar coordinates (r,θ) and (r',θ') with θ measured clockwise from the y axis, then the x and y velocities are given by

$$u_x = (r'-r)\sin\theta + r[\theta'-\theta]\cos\theta$$

$$u_y = (r'-r)\cos\theta - r[\theta'-\theta]\sin\theta$$

Using these velocity estimates in equation 1, we would obtain (using Figure 2) for a clockwise rotation of θ per unit time

$$\varepsilon_{11} = \varepsilon_{22} = \varepsilon_{12} = 0$$

$$w = [\theta'-\theta]$$

For the general case of many points utilizing least-squares equations based on Equations 1, it can be shown (Hibler et al., 1974) that adding a constant rotation to all angles only changes the vorticity.

Besides the special example considered here, this rotation effect can be illustrated by actual data. Such an illustration is given in Figure 3, where various rotational errors in the coordinate transfer of five common ice features between two LANDSAT images was purposely added. As can be seen, in agreement with the simple example of Figure 2, rotations of 3° can cause significant undesirable effects.

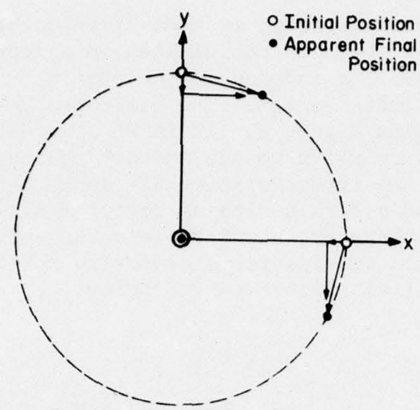


Figure 2. EFFECT OF SPURIOUS ROTATIONS ON ESTIMATED VELOCITIES

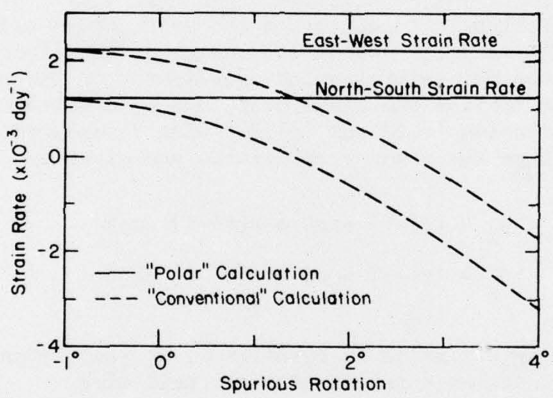


Figure 3. EFFECT OF SPURIOUS ROTATIONS ON ESTIMATED STRAINS

TABLE IV. APPARENT STRAINS ON LAND MASSES.

Units: Percent per day

Photo Pair	$\dot{\varepsilon}_{xx}$	$\dot{\varepsilon}_{yy}$	Shear	Vorticity
1	-0.069 ± 0.106	-0.276 ± 0.087	0.044 ± 0.069	0.063 ± 0.069
2	-0.178 ± 0.041	-0.033 ± 0.108	0.247 ± 0.058	-0.386 ± 0.058
3	0.024 ± 0.049	0.098 ± 0.053	-0.246 ± 0.036	0.143 ± 0.036
4	-0.241 ± 0.104	0.118 ± 0.098	0.108 ± 0.072	-0.051 ± 0.072
5	-0.142 ± 0.046	0.159 ± 0.053	0.109 ± 0.035	0.294 ± 0.035
6	-0.020 ± 0.157	0.402 ± 0.089	-0.078 ± 0.090	0.125 ± 0.090
RMS	0.139	0.219	0.159	0.215

In using this "polar" technique it should be noted that as long as one chooses one of the points as the origin, where the center of rotation is located has no effect on the results. This is because all lines connecting points will rotate by the same amount regardless of where the center of rotation is located. This will not, however, be true if one chooses for the origin some arbitrary point which may not actually represent a point on the ice.

Although the above procedure allows strain estimates to be independent of coordinate transfer errors, there will nevertheless still be some strain errors because of the registration error in marking common features and the non-linearities in the images. Besides being dependent on such factors, vorticity estimates additionally depend on errors in the orientation estimates of the coordinate systems on the two images.

To make a direct estimate of these errors we calculated least-squares strain and vorticity for the photo pairs used in the above transferral study. The results are shown in Table IV where we list the average strain rates and vorticities (which should be zero since there has been no motion) together with the inhomogeneity errors. As can be seen, on the average the strains are of the order of 0.1 to 0.2% per day which would represent a 0.2 km variation over 100 km, the approximate size of the arrays we were using.

However, not all the error can be attributed to random errors such as the registration errors. If this were the case then the average strain rates in Table IV would cluster around zero with the error being somewhat larger than the average strain. A more consistent way to interpret the results in Table IV would be to say that in addition to registration errors there are certain distortions in the photos. Assuming such distortions are approximately linear, the estimated strain would be equal to the average distortion with the residual error indicative of the registration error. For the six photos analyzed the average residual error is 86 m which is almost exactly the stated resolution (80 m) of the LANDSAT multispectral scanning system. The rest of the strain can be accounted for by saying that distortions induce about 100 m errors per 100 km. Consequently as a practical manner for estimating experimental errors in strain we can assign equal errors of about 100 m to the registration of points (which is in agreement with Colvocoresses (1974) estimates of geometric fidelity) and to image nonlinearities over distances of 100 km.

With regard to vorticity errors the rms vorticity in Table IV was only a little larger than the rms strain rate indicating that rotation effects were relatively minor. However, comparisons of the angles of the line of longitude passing through the center of a LANDSAT image, as obtained from different lines longitude marked on the image, indicate that the estimated andles often differ by 0.01 radian. This effect is somewhat ameliorated by taking the average estimated angle from two

longitude lines located as near to the image center as the image tic marks allow. Still, because of such errors, it would seem safer to assume the experimental vorticity error to be of the order of 0.5% per day.

To illustrate the application of these techniques to actual sea ice drift and deformation measurements, we examined three sequences of images from March 1973 in the region 78°N', 170°W. The starting position and day for each sequence is shown in Figure 4. Seq. 11 consisted of 7 images; Seq. 12, 6 images; and Seq. 13, 4 images. Four to six common ice features were digitized on each sequential image pair and the average drift and deformation calculated. The drift rates are shown in Figure 5. The westward drift rates generally decrease as one moves to the north, a fact which is in general agreement with the clockwise motion of the Pacific Gyre. Also the drift rates are on the average several kilometers a day which is larger than the observed transferral error of about 1 km per day. In general, these drift rates also agree with average drift rates of ice islands which are found to typically drift about 3.6 km/day in this region (Dunbar and Wittmann, 1962).

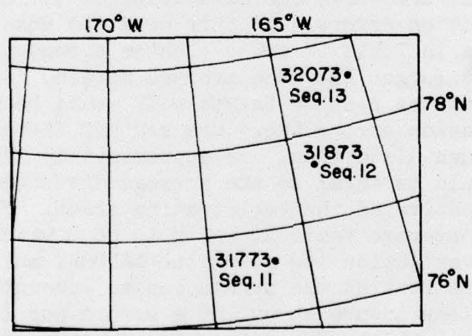


Figure 4. LOCATION OF INITIAL IMAGES IN SEA ICE IMAGE SEQUENCES

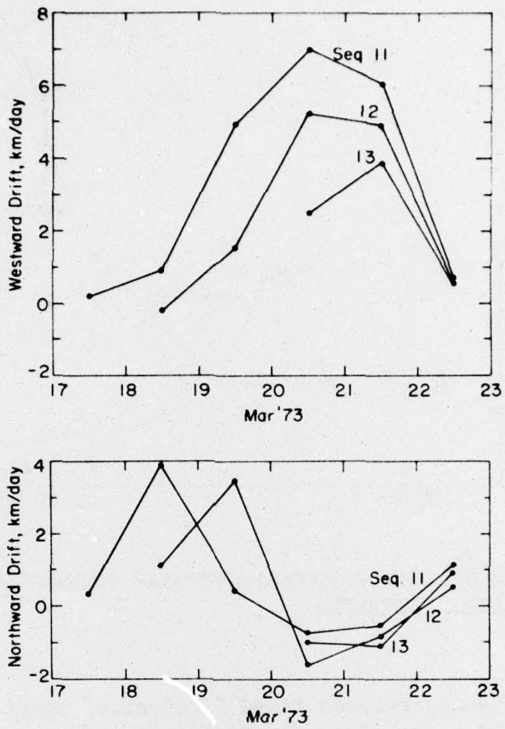


Figure 5. DRIFT RATES FROM SEA ICE IMAGE SEQUENCES

DEFORMATION RATE ESTIMATES FROM AERIAL IMAGERY

Because of its regular orbit, LANDSAT produces imagery which has a consistent orientation and linearity that makes it quite useful for estimating deformation rates. Aerial imagery unless corrected by photogrammetric techniques will have orientation differences due to changes in both the altitude and orientation of the aircraft during the reconnaissance run. To obtain some estimates of how well such uncorrected imagery can be used to measure distance changes bewteen ice features, and hence strain, we have utilized a series of aerial photos take at 9144 m (30,000 ft) by the NASA Convair 990 in April 1975 over the AIDJEX main base camp. On the ice two 40' by 40' black cloth targets were constructed and placed approximately 7 km apart. The changes in the distance between these two targets were measured to an accuracy of $\pm$ 2 meters using two theodolites separated on a baseline of $\approx$1.5 km in length.

Using six sequential images over the camp relative distance changes between the targets were estimated by comparing the target

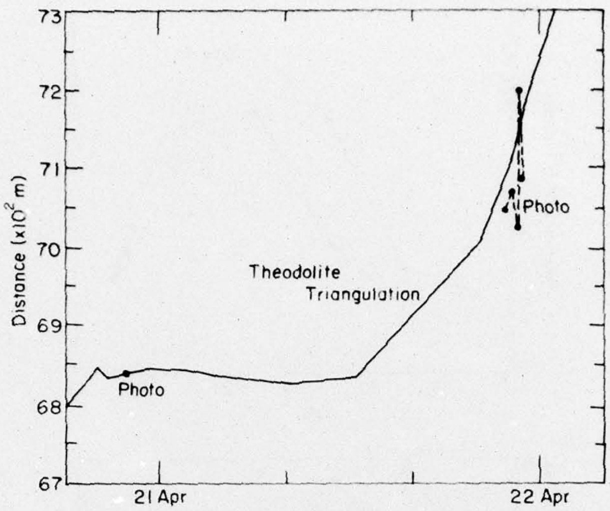


Figure 6. COMPARISON OF PHOTOGRAPHICALLY ESTIMATED DISTANCES TO ACTUAL DISTANCES

distances to distances between fixed "immovable" points on undeformed areas of a multiyear ice floe. In particular, 3 non parallel lines several kilometers in length were identified on a given floe. The average ratio of the lengths of these lines as determined from one photo in the sequence to their lengths as determined in an earlier photo was determined and used as a correction factor to be applied to the distance between the visual targets. The comparison of actual and photo estimated distances are given in Figure 6, where we have assumed the target distance on the first photo to be equal to the actual distance. As can be seen, the photo distances show a spread of about 100 m or 1.5% at 7 km. Although this is a significant error it is still small relative to the actual distance change between the targets which was several hundred meters ($\approx$ 5%). Another estimate of this type of error was made by examining the variation from photo to photo of the ratios of the three fixed calibration lines among themselves. If there were no errors, these ratios would not change, whereas in practice the standard deviation over 6 photographs varied from 1.7% to 2.2%.

Consequently, these limited results suggest that 2% is a reasonable estimate for the error in measuring distance from high quality aerial imagery without photogrammetric corrections. Because actual sea ice distance changes are often 10% when measured on the small scale, such error can occasionally be neglected. An example of such a case would be a study where only the widths of the leads are important.

CONCLUSIONS

We believe that this study has shown that, when analyzed with appropriate techniques, LANDSAT imagery is adequate for estimating sea ice drift rates at locations far from land. The transferral geometry described in this paper gives a simple and rapid way to transfer coordinates from one image to another with the errors in the transferral equations being negligible over the transferral distances used. In general, the errors in the transferral process are dominated by the deviation of the actual image centers from their stated centers. The effect of such uncertainties, however, is not enough to mask effects caused by typical sea ice drift.

As regards deformation rates, typical results show that it is important to use a least squares procedure that is independent of rotation effects. Also, the magnitude of errors in strain rates, due to experimental errors and non-linearities in the ice velocity field, suggest that two day averages of strain rates should be used when estimating deformation rates from LANDSAT images. When estimating deformation rates from uncorrected aerial imagery of sea ice, typical errors appear to be of the order of 2% which although large are again less than observed differential distance changes as measured on a small scale (several kilometers).

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